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## Modeling the 2008 Ultrasonic Benchmark Problems

Lester W. Schmerr Jr.

*Iowa State University*, [lschmerr@iastate.edu](mailto:lschmerr@iastate.edu)

Ruiju Huang

*Iowa State University*

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# MODELING THE 2008 ULTRASONIC BENCHMARK PROBLEMS

Lester W. Schmerr, Jr.<sup>1,2</sup> and Ruiju Huang<sup>1</sup>

<sup>1</sup>Center for NDE, Iowa State University, Ames, IA 50011, USA

<sup>2</sup>Dept. of Aerospace Eng., Iowa State University, Ames, IA 50011, USA

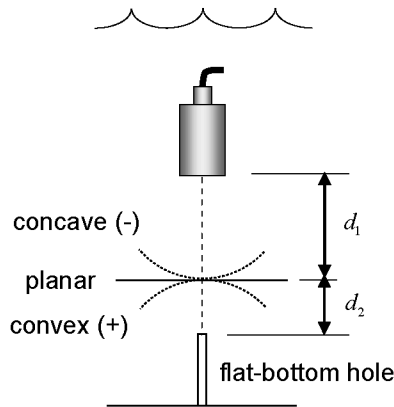
**ABSTRACT.** Two studies were part of the 2008 QNDE ultrasonic benchmark session. The first study considered the effects of the curvature of a fluid-solid interface on the pulse-echo immersion response of a flat-bottom hole. This was a re-examination of a problem considered in the 2007 benchmark but with a well-characterized transducer and a different set of testing conditions. The second study considered the response of a series of side-drilled holes at different depths. Here we will summarize the results obtained at the Center for NDE (CNDE), Iowa State University, for these two benchmark problems.

**Keywords:** Ultrasonic Benchmark, Curvature Studies, Side-Drilled Hole, Flat-Bottom Hole, Multi-Gaussian Beam Model, Kirchhoff Approximation, Separation of Variables Method

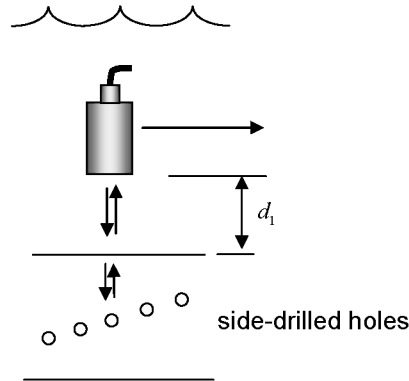
**PACS:** 43.35.Yb

## INTRODUCTION

One of the problems considered at the ultrasonic benchmark session of the 2007 Review of Progress in Quantitative NDE meeting was the pulse-echo response of a flat-bottom hole (FBH), as measured through a curved fluid solid interface in an immersion test setup (Fig. 1). This benchmark study was a comparison of model-based results to experiments for various interface curvatures. Modeling results from various groups around the world [1] all showed larger than expected differences with the experimental results so that it is important to understand the source(s) of those differences. Thus, the 2008 ultrasonic benchmark study discussed here was conducted with the same curved test block samples but with a more thoroughly characterized transducer and slightly different test conditions to try isolate the sources of error seen in the 2007 benchmark. These changes from the 2007 benchmark are discussed in more depth in a summary paper in this proceedings [2]. As in the 2007 benchmark study, in 2008 the experiments were conducted at the Commissariat à l'Energie Atomique (CEA) in France using a spherically focused transducer to inspect a number of 0.8 mm diameter (#2) FBHs placed in aluminum blocks. For all tests the water path distance was fixed at the value  $d_1 = 75 \text{ mm}$  (see Fig. 1) while the depths of the FBHs had the values  $d_2 = (6.35, 12.7, 19.05, 25.4, 38.1, 50.8, 76.2) \text{ mm}$ . One block had these FBHs located below a planar interface while two blocks contained a convex surface ( $R = +50.8 \text{ mm}$  and  $+203.02 \text{ mm}$  radius) and two others had a concave



**FIGURE 1.** The geometry considered in both the 2007 and 2008 ultrasonic benchmark curvature studies where a transducer in an immersion setup measures the pulse-echo response of an on-axis flat-bottom hole at normal incidence through a cylindrically curved interface.



**FIGURE 2.** The geometry of the side-drilled hole study for the 2008 benchmark where a focused transducer is scanned parallel to the surface of a steel block containing 2 mm diameter side-drilled holes at different depths.

surface ( $R = -50.8 \text{ mm}$  or  $-203. \text{ mm}$ ). For a complete description of all the parameters specified for this test, see the summary paper in this proceedings [2]. The amplitudes of the rectified A-scan signals were measured for all the FBHs considered and a table of amplitude ratios (in dB) was prepared, where the ratios were obtained by dividing a given FBH response by that of a reference case. The reference case here was the FBH located 12.7 mm below the surface of the block with a planar interface. The objective of this study, as in the 2007 benchmark, was to compare model-based predictions of these amplitude

ratios to their experimental values.

In the 2008 ultrasonic benchmark session we also considered the pulse-echo responses of a series of side-drilled holes in a steel block, as shown in Fig. 2. In this case the same focused transducer as used in the FBH study was scanned parallel to the surface of the block and the maximum amplitude responses of each hole measured. Using one of these holes as a reference, the relative maximum response of each hole to that reference was calculated in dB. Again, the objective of the study was to compare these measured relative amplitudes to model-based predictions.

## CURVATURE STUDY

In the curvature study of the 2008 benchmark, we used the same modeling approach described in the 2007 benchmark. The flat-bottom hole (FBH) was divided into triangular elements and the response of each element obtained by the use of the Thompson-Gray measurement model [3]. Summing all these element contributions then gives the frequency spectrum of the measured FBH signal,  $V_R(f)$ , as

$$V_R(f) = \beta(f) \sum_n [\hat{V}^2(f, \mathbf{x}_n)] [A_n^{P:P}(f)] \left[ \frac{2}{-ik_{p_2} a^2} \frac{\rho_2 c_{p_2}}{\rho_1 c_{p_1}} \right] \quad (1)$$

Although, the FBH size here was relatively small, the triangular elements used in Eq. (1) do account for any small variations of the incident beam field that might be present over the face of the FBH. Here  $n$  denotes the  $n$ th triangular element and  $A_n^{P:P}(f)$  is the pulse-echo plane wave P-wave far-field scattering amplitude of the  $n$ th element, which is calculated by use of the Kirchhoff approximation. The calculation of the normalized velocity  $\hat{V}(f, \mathbf{x}_n)$  at the centroid,  $\mathbf{x}_n$ , for each element was performed here with the use of a multi-Gaussian beam model [3]. The parameter  $k_{p_2} = 2\pi f / c_{p_2}$  is the wave number for the P-waves propagating in the aluminum and  $a$  is the radius of the transducer. The quantities  $(\rho_1, \rho_2)$  are densities of the water and the density of the block, respectively, and  $(c_{p_1}, c_{p_2})$  are the corresponding P-wave speeds for the water and block. The  $\beta(f)$  function is the system “efficiency factor” which characterizes all the electrical and electromechanical parts of the measurement system [3]. For a more complete specification of the values of these parameters and the system efficiency function used in the study, see the summary paper [2]. Using Eq. (1) and a Fast Fourier Transform, the time domain A-scan response of the FBH can be calculated and the amplitude of the rectified A-scan signal determined. These amplitude values were the primary model-based results obtained in this study. The objective of the 2008 benchmark study was to compare the matrix of model-based amplitude results obtained for different hole depths and curvatures with the corresponding matrix of values obtained from experiments.

Table 1 shows the differences obtained (in dB) between the model-based values we obtained and the experimental values. The cases in that table are shaded where there is more than a 2 dB difference between the model-based results and experiments. Because the multi-Gaussian beam model uses the paraxial approximation which breaks down when the interface is too highly curved it might have been expected that the  $R = \pm 50.8 \text{ mm}$  interfaces would exhibit the largest differences for all hole depths.

**TABLE 1.** The differences (in decibels) between the peak-to-peak amplitude ratios obtained from models to the experimentally observed values for the different fluid-solid interface curvatures shown and for different flat-bottom hole depths (in mm). Differences larger than 2 dB are shown in shaded in the table.

	6.35	12.7	19.05	25.4	38.1	50.8	76.2
R = $\infty$ (planar)	0.5	0	-0.4	-0.5	0.6	0.0	1.4
R = 50.8 mm (concave)	0.3	0.9	0.0	-2.3	-2.7	-0.4	-2.7
R = -50.8 mm (convex)	1.7	0.2	-0.1	-0.3	-0.7	-0.1	0.7
R = 203 mm (concave)	2.0	1.1	0.7	0.6	1.0	0.3	-0.4
R = -203 mm (convex)	0.7	0.2	0.0	0.2	-0.4	-0.9	-1.0

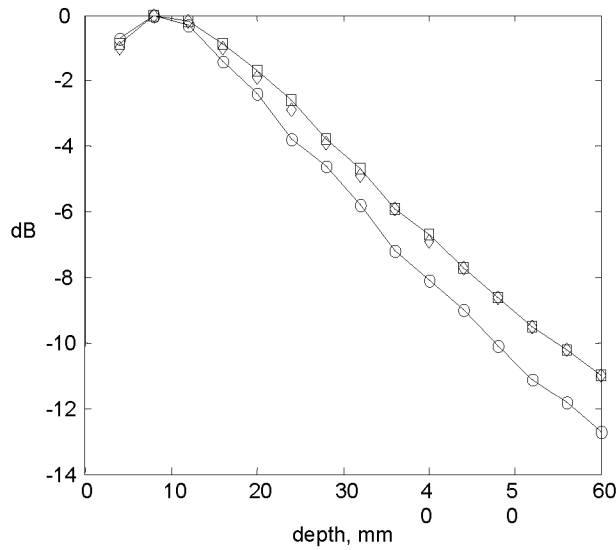
However, as Table 1 shows, relatively large errors are only evident at certain hole depths and only for the R = +50.8 mm case. This suggests that errors other than paraxial errors may be present. It can also be seen from Table 1 that, with the exception of the FBH at the smallest depth for the 203 mm radius concave interface case, all of the other cases are in good agreement, with most differences between the model-based results and experiments significantly smaller than 1 dB. This is in contrast to the 2007 benchmark study where large ( $> 2$  dB) differences were seen in a variety of cases. One likely reason for the better agreement found in the present study is that in 2008 we used a well-characterized transducer whose model parameters generated wave field values that matched well with the actual beam generated by the probe. This is further discussed in the summary [2].

## SIDE-DRILLED HOLE STUDY

In the side-drilled hole (SDH) study, the density and compressional wave speed of the water were taken as  $\rho_1 = 1 \text{ gm/cm}^3$ ,  $c_{p1} = 1486 \text{ m/sec}$ , respectively. The corresponding density and compressional and shear wave speeds of the steel block were given as  $\rho_2 = 7.8 \text{ gm/cm}^3$ ,  $c_{p2} = 5900 \text{ m/sec}$ ,  $c_{s2} = 3230 \text{ m/sec}$ . The water path  $d_1 = 75.0 \text{ mm}$  (Fig. 2) and the side-drilled holes all had a radius of 1 mm and were located at depth ranging from 4.0 to 60.0 mm. The same transducer used in the curvature study was used here and scanned parallel to the surface of the block. The maximum amplitudes of the rectified A-scan signals, when the transducer was located over each SDH, were measured. The ratio of these amplitudes to a reference case (taken here as the amplitude of the SDH response at a depth of 8 mm) were calculated in dB. The objective was to compare model-based predictions of these responses to the experimentally measured values.

The measurement model used to here is similar to the one described in the 2007 study where the frequency spectrum of the received voltage,  $V_R(f)$ , is given by [3]:

$$V_R(f) = \beta(f) \left[ \int_L \hat{V}^2(f, z) dz \right] \left[ \frac{A^{P,P}(f)}{L} \right] \left[ \frac{2}{-ik_{p2}a^2} \frac{\rho_2 c_{p2}}{\rho_1 c_{p1}} \right] \quad (2)$$



**FIGURE 3.** The pulse-echo P-wave response of side-drilled holes at different depths. Measured responses (circles) versus model-based results using the Kirchhoff approximation (squares) or the method of separation of variables (triangles) to model the SDH scattering amplitude.

where  $\beta(f)$  is the system efficiency factor,  $\hat{V}(f, z)$  is a normalized velocity amplitude of the waves incident on the SDH,  $A^{P:P}(f)$  is the plane wave pulse-echo far-field scattering amplitude (for P-waves) of the SDH,  $L$  is the length of the SDH, and  $a$  is the transducer radius. The parameter  $k_{p2} = 2\pi f / c_{p2}$  is the wave number for P-waves propagating in the block. The velocity amplitude was obtained with the use of a multi-Gaussian beam model and the far-field scattering amplitude was modeled using the Kirchhoff approximation [3]. The transducer radius and focal length were taken as the same effective values used in the curvature study. The efficiency factor was obtained experimentally by using Eq. (1) and the measured waveform in the reference case and calculating the efficiency factor via standard deconvolution procedures [3].

The differences (in dB) between the model-based results (using the Kirchhoff approximation for the scattering amplitude) and the experimental results are given in Table 2. It can be seen that although there is relatively good agreement between the model-based and experimental results, there is a growing difference with depth. This trend can be clearly seen in Fig. 3 where we have plotted both the experimental results and model-based results versus SDH depth. To ensure that the Kirchhoff approximation was not responsible for any of these differences, we also calculated model-based results using the method of separation of variables to determine the far-field scattering amplitude in Eq. (2) [3], which also accounts for any creeping waves that may exist in the SDH response. It can be seen from Fig. 3 that there was no significant change in the model-based predictions. One source for these growing differences may be ultrasonic attenuation in the steel block. This could be checked by making an independent measurement of the attenuation of P-waves but for the

**TABLE 2.** Differences in decibels (model – experiment) between the model-based signals received from a side-drilled hole and the experimentally measured values for the 2008 benchmark study.

SDH depth (mm)	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60
dB diff	-0.3	0	0.1	0.4	0.5	0.9	0.7	0.9	1.3	1.2	1.3	1.5	1.6	1.6	1.7

benchmark study such measurements were not available.

## SUMMARY AND DISCUSSION

In the 2008 benchmark study, model-based predictions of the pulse-echo P-wave responses of a FBH as measured through a series of curved interfaces generally showed good agreement with experiments. This is in contrast to the large differences seen in the 2007 benchmark study [1]. Most of these differences from the 2007 benchmark are likely due to the use of a well-characterized transducer in the present study, showing the importance of using transducer parameters that accurately predict the behavior of the sound beam of the transducers being used in an inspection.

For the SDH study conducted as part of the 2008 benchmark, the model-based predictions predicted well the overall behavior of the responses of a series of flat-bottom holes at different depths in a steel block, but with a growing error with depth that may be due to the ultrasonic attenuation of the block.

## ACKNOWLEDGEMENTS

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